Chapter One

Introduction

1.1 Overview

Through a number of exercises, national and international, disciplinary and interdisciplinary, researchers have established plans for systematic carbon cycle studies. A landmark in U.S. planning efforts was the writing of the U.S. Carbon Cycle Science Plan (CCSP), published in 1999 (Sarmiento and Wofsy, 1999).

The CCSP defined two fundamental questions about the carbon cycle: What has happened to the carbon dioxide that has already been emitted by human activities (past anthropogenic CO_2)? And, what will be the future atmospheric CO_2 concentration trajectory resulting from both past and future emissions? In connection with these questions, the CCSP offered two hypotheses, consistent with a significant body of scientific evidence: First, a large terrestrial sink for anthropogenic CO_2 exists in the Northern Hemisphere. And second, the oceanic CO_2 inventory will continue to rise in response to increasing atmospheric partial pressure of CO_2 (pCO_2), but at a slower rate, owing to changes in ocean circulation, biology, and chemistry.

To address these questions and test these hypotheses, the CCSP formulated five long-term (5- to 10-year) goals and five short-term (5-year) goals. The first two long-term goals involve long-term observations: developing an observational infrastructure, and documenting the partitioning of CO_2 sources and sinks among oceanic and terrestrial regions. The remaining three long-term goals are aimed at greater process-level understanding and predictive capability. These latter two capabilities can be advanced only if process-level models can be tested against extensive, critical observations. The first two short-term goals rely primarily on observations: quantifying and understanding the Northern Hemisphere terrestrial carbon sink, and quantifying and understanding the uptake of anthropogenic CO_2 in the oceans. Accordingly, the CCSP targets North America and Eurasia as key continental areas. It identifies the North Atlantic and North Pacific as top priority ocean basins for air-sea flux studies. The Southern Ocean is also identified as a critical region in the long-term plan, because this region may be especially affected by climate change.

Inherent in the CCSP is the idea that an integrated approach involving a comprehensive and simultaneously executed observing strategy is essential to constrain the contemporary carbon cycle and to make meaningful forecasts (Appendices E and F). In November 1999, the NOAA Office of Global Programs commissioned the writing of an implementation plan for oceanic and atmospheric CO_2 observations, as a contribution toward implementing the U.S. Carbon Cycle Science Plan. This document presents that plan.

As envisioned in the commissioning letter, the plan presented here is not comprehensive. It deals with large-scale measurements of CO_2 and related properties in the ocean and atmosphere. "Related properties" are a limited set of gases and solutes diagnostic of CO_2 sources and fluxes. This plan requires mechanistic insight from local process studies of the land and ocean biospheres to achieve its goals. It also requires satellite data defining a wide range of physical and biogeochemical properties in space and time. The land biosphere, ocean biosphere, and satellite studies are all subjects of continuing independent planning. This document complements those plans but does not attempt to duplicate them.

1.2 Background

Combustion of fossil fuels, and the attendant CO_2 increase, are likely to have a significant impact on Earth's climate. At the global scale of interest here, the main issue is the radiative forcing of CO_2 (and of other greenhouse gases), and the implications of this forcing for the global climate system. Related issues are the effects of atmospheric CO_2 on the biosphere, and the impacts of climate change on human endeavors.

Determining the fate of fossil fuel-derived CO_2, with its consequences for the rate at which the atmospheric CO_2inventory rises, is central to understanding and predicting the environmental effects of combustion. Processes relevant to the carbon cycle span the range of scales from molecular to global. They also include a wide range of biological, oceanographic, and atmospheric phenomena, as well as interactions between humans and the environment. Studies of the carbon cycle must adequately address the entire range of issues. The strategy for doing so requires studies at four different scales. The first is the scale of fundamental processes. In biology, this scale is at the molecular, cellular, or plant level. In ocean and atmospheric physics, it includes studies of turbulence and boundary layers. The second scale is that of the local ecosystem. Examples of such studies include those of the Long-Term Ecosystem Research (LTER) sites, free air CO_2 enrichment experiments (FACE), and the time-series and process studies of the Joint Global Ocean Flux Study (JGOFS).

The third scale is that of coherent ecosystems, spanning distances on the order of 10^3 km. This scale is accessed by studies of biogeochemical properties of the sea surface and of atmospheric gradients over the continents. The fourth scale encompasses spatial areas from continents and ocean basins to the globe. In research at these large scales, one attempts to assess changing CO_2 inventories and fluxes from observations of CO_2 in the ocean and atmosphere.

Acquiring a process-level understanding of large-scale fluxes is a critical goal of carbon cycle studies, and a requirement for prediction. Achieving this understanding begins with observations. It must also include modeling, which allows the quantitative representation of processes and thus scaling the implications of process studies. Carbon cycle models of the land biosphere represent the fundamental processes of photosynthesis and autotrophic and heterotrophic respiration. These models are formulated in the context of climate models, and can be used to calculate carbon fluxes at large scales.

Carbon cycle models of the ocean biosphere represent the food chain. They are formulated in the context of ocean and atmospheric physics models, which include implications for the transport of bioactive elements. Scaling and achieving process-level understanding both rely critically on satellite data, which allow us to closely track many biosphere properties, as well as the physical systems with which the biosphere interacts, over wide scales of time and space.

Atmospheric observations of the CO_2 distribution were pioneered by C.D. Keeling in 1957, and were continued by him and others at laboratories around the world. Atmospheric measurements of CO_2 constrain the net change in the atmospheric inventory. Sources and sinks of CO_2 to the atmosphere include input from combustion, exchange with the land biosphere, and exchange with the oceans. Deducing land-air and land-sea fluxes from CO_2 distributions is most straightforward at the global scale, where the CO_2 increase is equal to fossil fuel addition minus uptake by the ocean and land biosphere. Attempts are progressing to establish regional mass balances at the scale of a hemisphere and a continent/ocean basin (Fan *et al.*, 1998; Kaminski *et al.*, 1999; Rayner and Law, 1999; Bousquet *et al.*, 2000), but are still marked by large uncertainties. Complementary atmospheric measurements, notably the $\delta^{13}C$ of CO_2 and the O_2/N_2 ratio of air, allow one to partition CO_2 uptake into land and ocean sinks at the global or hemispheric scales. Atmospheric measurements constrain seasonal net production of the land and ocean biospheres on an annual timescale. They also constrain annual global and regional sequestration of fossil fuel CO_2.

Observations of the distribution of CO_2 and related properties in the ocean interior permit one to track the increasing inventory of fossil fuel CO_2. Beginning in 1972, the Geochemical Ocean Section Study (GEOSECS) made the first set of accurate and geographically comprehensive measurements that could be used in this way (Bainbridge, 1981; Broecker *et al.*, 1982; Weiss *et al.*, 1983). The global survey of the World Ocean Circulation Experiment (WOCE)/JGOFS accumulated a large and important data set in the 1990s. These and related studies made fundamental contributions to our understanding of patterns and rates of ocean circulation. They also contributed to a comprehensive picture of the oceanic distribution of bioactive chemicals and rates of biological transformations.

The fossil fuel CO_2 content of ocean interior waters is superimposed on the large background concentration of CO_2 in seawater. Chen and Millero (1979) and Brewer (1978) first proposed methods to separate the two CO_2 pools and calculate fossil fuel inventories. Gruber (1998) and Sabine *et al.* (1999) have recently modified the earlier approaches to compute the distribution of fossil fuel CO_2 in the Atlantic and Indian Oceans, respectively. It is thus possible to accurately discern inventory changes directly over periods of about 10–20 years. The $\delta^{13}C$ of total dissolved inorganic carbon (TCO_2) in seawater is influenced by the distinctive signature of fossil fuel carbon, giving a complementary tracer of the oceanic distribution of fossil fuel CO_2 (Quay *et al.*, 1992).

Ocean CO_2 uptake results from the difference in the partial pressure of CO_2 between the atmosphere and surface seawater. One can calculate the rate of CO_2 invasion from the partial pressure difference and the gas exchange rate, which has generally been parameterized as a function of wind speed. In principle, calculating ocean CO_2 uptake is therefore straightforward. Unfortunately, sea surface pCO_2 is highly variable in time and space, and estimates of the gas exchange coefficient are uncertain. Thus the problem is daunting. Takahashi *et al.* (1999) have assembled a database of over 700,000 individual sea surface pCO_2 determinations that give basin- and global-scale estimates of climatological air-sea fluxes. Data coverage is uneven in time and space, however. Uncertainties remain large, particularly for constraining the global net flux. Temporal and spatial variability are so large that only now, for some areas of the ocean, can we go beyond creating a climatology, and examine interannual variability in air-sea fluxes. In principle, however, it is possible to constrain sea surface pCO_2 on seasonal timescales, and to study interannual variability on regional scales.

These three approaches to constraining the balance of fossil fuel CO_2 (involving atmospheric, sea surface, and ocean interior CO_2 measurements) give redundant information. For example, atmospheric measurements of CO_2, ocean interior measurements of TCO_2, and sea surface CO_2 measurements each allow one to calculate the rate of oceanic CO_2 sequestration. This redundancy is an absolutely critical attribute of ongoing CO_2 observations, because uncertainty associated with each approach is large. In addition, of course, observations based on CO_2 complement observations from a wide range of other approaches based, for example, on land carbon inventories and process studies of land and ocean biospheres.

Each observational approach also gives unique information about CO_2 fluxes, both fossil and natural. Atmospheric measurements give definitive information about the fossil fuel burden of the atmosphere. They integrate most rapidly over large spatial scales, thereby giving the best index of large-scale seasonal fluxes and interannual variability. Atmospheric measurements also provide unique information about continent-scale rates of CO_2 uptake by the land biosphere. Sea surface pCO_2 measurements, together with essential and problematic estimates of gas exchange coefficients, constrain the regional and temporal distribution of ocean uptake. Ocean interior concentrations of anthropogenic CO_2 reflect the regions where fossil fuel CO_2 is entering the oceans and its subsequent transport.

Finally, the three approaches give process-level information about the biosphere and its response to the evolution of Earth's climate. Seasonal variations in the CO_2 concentration, isotopic composition of CO_2, and O_2/N_2 ratio of air reflect mean rates and interannual variability of photosynthesis and respiration on land and in the oceans. Long-term data sets record the changing response of the biosphere to varying climate. Notable examples include net release of CO_2 by the land biosphere during most El Niño events (e.g., Keeling *et al.*, 1995), and increasing net seasonal production on land recorded by the increasing amplitude of the annual CO_2 cycle in the Northern Hemisphere (Myneni *et al.*, 1997). Sea surface pCO_2 data give a measure of net community production in the upper ocean. The link derives from the removal of TCO_2 during net production, which drives down the partial pressure of CO_2 in seawater. Sea surface pCO_2 thus quantitatively constrains net production, after one corrects for the injection of subsurface waters, which are rich in CO_2 and supply essential nutrients, as well as for air-sea exchange. Finally, ocean interior studies give the distribution of TCO_2, nutrients, and O_2 utilization deriving from metabolism of organic matter produced in the surface ocean. The concentrations of these constituents in the dark ocean may vary with time (e.g., Pahlow and Riebesell, 2000), particularly in the thermocline, which is ventilated on a timescale of decades. Such variations might be due to changing rates of net production, changes in the composition of organic debris that sinks and is oxidized, or variations in rates of ocean circulation and ventilation.

In summary, observations of CO_2 inventories and fluxes in the three realms combine to constitute a comprehensive CO_2 observing system for the Earth. In Chapters 2 through 5, we recommend a plan for specific aspects of this system.

1.3 Planning Activities

A committee of 14 scientists involved in observing and modeling the distribution of CO_2 in the atmosphere and ocean was established to write this implementation plan for carbon observations, in the context of the CCSP. We first met at Princeton University in February 2000, to discuss the nature of the research and the plan itself.

At that time, the group took several key decisions. First, we decided to recommend continuation of all three approaches now used to determine transfers and inventories of anthropogenic CO_2: atmospheric observations, ocean interior observations, and determinations of pCO_2 in surface water that allow the calculation of air-sea fluxes. We believe that the large uncertainties associated with each approach make redundancy essential. We also felt that all three approaches must be continued because each gives essential process-level information.

Second, we decided to base our recommended observing systems largely on objective criteria derived from modeling studies, to the extent that this is possible given inherent limitations of this approach. Gloor *et al.* (2000) first used objective design to help identify the distribution of atmospheric CO_2 sampling sites that would give the most accurate estimate of annually averaged regional carbon fluxes. In this report, we examine the potential benefits of additional sampling, to plan an enhanced air sampling network. We also extensively analyzed results of sea surface CO_2 measurements to formulate a strategy for this component.

Third, we analyzed how the accuracy of calculated ocean interior CO_2 inventories depends on sampling density, and used these results to formulate a measurement strategy. Network design studies were carried out by P. Tans and B. Stephens for atmospheric measurements, T. Takahashi, P. Murphy, C. Sweeney, H. Gnanadesikan, and J.L. Sarmiento for sea surface pCO_2 studies, and C. Sabine, S. Doney, and R. Feely for ocean interior studies. Their work involved original research that made an important contribution to this report.

Fourth, we endorsed the Northern Hemisphere focus of the CCSP, with two modifications. We extended the North Pacific to include the equatorial Pacific, which is responsible for much of the interannual variability in the growth rate of the atmospheric CO_2 inventory. We also assigned the Southern Ocean a high priority for short-term as well as long-term studies. Strong arguments suggest that the Southern Ocean will very likely be especially affected by climate change. This critical but remote region is, paradoxically, quite accessible for sea surface pCO_2 observations, because a number of ships traverse its waters periodically to resupply Antarctic bases.

Fifth, we decided that the implementation plan for CO_2 observations should include a biennial assessment on the state of the carbon cycle. This report will summarize the status of carbon cycling (e.g., atmospheric CO_2 growth rate, ocean uptake rate) and its evolving dependence on climate. It will also summarize the status of studies of the carbon cycle, with emphasis on observations and relevant modeling.

Lastly, the committee recognized that most components of a truly global carbon observing system cannot be implemented in a single step. The planning, therefore, focused on the idea of an initial 5-year period in which key observational programs (some at regional/basin scale) are initiated. During this time, other infrastructure, development, and planning issues will be addressed (e.g., testing and evaluation of autonomous measurement systems, collection of data required to confidently design aspects of the observing system). The knowledge gained during the first 5 years would then be applied in a second 5-year phase in the expansion to a fully global system. Planning of CO_2 observations in the ocean interior is an exception: we are currently able to formulate a long-term plan for this work, and recommend such a plan here.

Following the Princeton meeting, members of the committee prepared and edited draft chapters outlining the atmospheric CO_2 measurements, sea surface pCO_2 measurements, and ocean interior measurements that would comprise the observation program. We then organized a meeting in Boulder, Colorado, in November 2000, to review these draft chapters.

About 45 scientists from university research laboratories, government laboratories, and federal funding agencies attended the Boulder meeting. The meeting began with a plenary session presenting, critiquing, and discussing each chapter of the implementation plan. It included a discussion of the role of modeling. This session was followed by breakout meetings dealing with the topics of individual chapters and related issues, interwoven with plenaries at which results of breakout sessions were discussed.

The consensus at the Boulder meeting confirmed that the CO_2 observing program should include atmospheric measurements, sea surface pCO_2 studies, and an ocean interior program. There were extensive discussions of the roles of modeling, remote sensing, and autonomous observations in the CO_2 observing system. There was also discussion of a broad range of details that are necessary for a successful plan. The meeting benefited tremendously from the very broad spectrum and depth of participants' expertise.

1.4 Structure of the Report

The document that follows contains three core chapters. They outline strategies for observing the distribution of CO_2 and its evolution in the atmosphere, the sea surface, and the ocean interior. A chapter on modeling CO_2 observations follows. The report does not outline a detailed strategy for modeling studies, but it does discuss the profound ways that models and data interact, and it outlines modeling advances required to improve our understanding of carbon fluxes. A brief chapter describing an annual report on the state of the carbon cycle comes next, and a short summary chapter closes the document.